THE DESIGN AND FATIGUE TESTING OF THE AOC 15/50 WIND TURBINE BLADE

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Abstract

Key design and manufacturing considerations in the development of the first prototype Atlantic Orient Corporation (AOC) 15/50 wind turbine blade are cited. This blade is a wood/epoxy composite design which incorporates a new family of NREL wind turbine airfoils. Collaborations among the wind turbine designer, blade designer, blade manufacturer, and the structural testing laboratory are illustrated in terms of the design process. Results show the merits of fatigue testing and how it was used to assess and qualify the AOC 15/50 blade. Test results are presented which were used to illuminate important material and design issues including identifying the relative importance of known stress risers, validating fabrication techniques, quantifying material size effects, and baselining strain measurements for field testing. The measured blade fatigue strength can also give the designers and manufacturers valuable information on actual fatigue life margins if compared to field test data.

Introduction

Use of the wood-epoxy composite construction system with the NREL advanced airfoils posed a number of new design challenges, due largely to the considerably more complex shapes of the inboard airfoils. This meant that some successful features of our earlier manufacturing experience could not be applied and, moreover, that certain areas of wood-epoxy composite blade design and manufacturing had to be advanced well beyond the previous state of development.

A central area of concern was the ability of the veneers to conform to the highly asymmetric inboard airfoil shape, and still make the transition to a more symmetrically shaped root. One characteristic of the Douglas fir veneer sheets, the primary structural component of the blade, is to resist compound bending. Veneer sheets are quite pliable across their width, which is perpendicular to their grain direction. In this direction it is generally not a problem to bend the veneer into the basic airfoil contours. However, the veneers are much stiffer along their length, which coincides with the sheet grain direction, so bending in that direction is considerably more difficult. Gentle curvature along the grain is not necessarily a problem, as the sheets are only 2.5 mm (. 1 in) thick, and are still somewhat flexible. The problem arises when there is a requirement to bend in both directions simultaneously. In this case, a considerable resistance to bending will be exhibited, just as it would for most rigid sheet materials. This characteristic can be readily demonstrated with a sheet of ordinary paper, which can be easily bent into conical or cylindrical shapes but will not accept domed or saddle shapes requiring double axis curvature.

Problems with compound curvature can be exhibited in many ways. A moderately thick stack of veneers may have enough bending resistance to preclude their formation into the desired shape under the limited forces available using vacuum bag lamination techniques. In less extreme cases, the veneers might form into the desired shape fairly well, but the bonding strength between layers may be compromised because of substandard compaction. Another complication is if there are joints in the region of compound curvature, these joints may shift and deform as the sheets attempt to conform to the complex shape resulting in decreased joint performance. In severe cases this may result in veneer splitting or overlaps that would greatly reduce joint performance.

A substantial part of the design process for wood-epoxy blades is to choose shapes and shape transitions that minimize compound curvature in the external blade shape, while still providing high aerodynamic efficiency. The complex geometry of the NREL inboard airfoil shapes push this facet of the design process well beyond previous limits. Although it was not felt that this would preclude or substantially limit use of a wood-epoxy fabrication system with the NREL airfoils, it was clear that new proof of performance beyond previous successful field experience would be warranted. A full blade fatigue test provided an excellent way to examine the effects of the many new design and manufacturing changes all at once, and demonstrated that the required mechanical performance levels were achieved.

AOC 15/50 Machine Design Characteristics

The AOC 15/50 turbine is a downwind, passive yaw, three-bladed rotor configuration. The rotor is 15 m (49.4 ft) in diameter and consists of a single piece cast hub supporting three wood-epoxy blades configured with NREL thick series airfoils. An aerodynamic brake is mounted at the end of each blade to provide torque reduction for both active braking and safety modes. The rotor is connected to an integrated gearbox, which serves as both the speed increaser and main structural member. A totally enclosed air over generator mounts directly to the high speed end of the gearbox. The generator is coupled with ground-based components which provide a dynamic braking device. A parking brake is attached to the free end of the generator. The complete drivetrain is on a three legged galvanized steel lattice tower with a hub height of 25 m (82.3 ft). The drivetrain is coupled to the tower though a turntable bearing which provides the passive yaw characteristics of the turbine. The actual tower-to-bearing interface is a one piece cast tower top. The guiding philosophy of the design was rugged simplicity, consistent with safety, efficiency, reliability, low noise, and minimum maintenance.

Features of the AOC 15/50 Turbine

þ 3 bladed, 15 m (49.4 ft), wood-epoxy rotor

þ Downwind, rigid hub, free yaw, (optional yaw damper)

þ 50 kW rating at 11 m/s

þ Cut-in at 3.7 m/s (8.28 mph)

þ Annual output (100% availability) 228,800 kWh at 8 m/s (17.9 mph)

þ Rotor speed at rated power 64 rpm

þ Rotor tip speed 50 m/s (111.8 mph)

þ NREL thick airfoils, 7.2 m (23.7 ft) blades, 137 kg (301 lbs) each

þ Electro-magnetic tip brakes for overspeed protection

þ Integrated gearbox with planetary gearing

þ 3 phase, 480 V induction generator, totally enclosed class F insulation, 1800 rpm - nominal

þ 3 leg bolted lattice tower, 24.4 m (80.3 ft)

þ Concrete foundation defined by site requirements

þ Microprocessor based control system

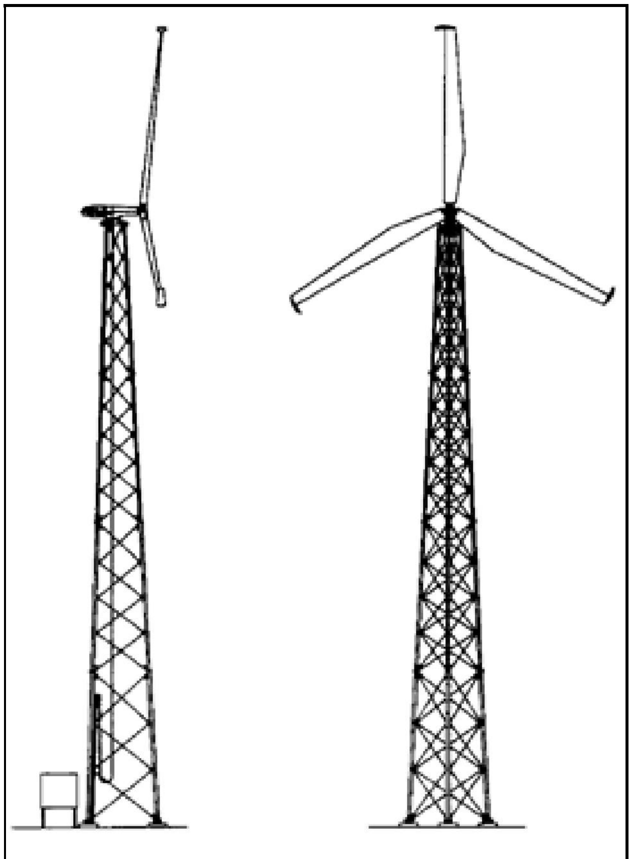

Figure 1. AOC 15/50 Wind Turbine

Test Motivation and Methodology

Since the inboard blade region must accommodate the geometric transition from the highly asymmetric NREL inboard airfoil to a more symmetric root shape, for efficient stud load transfer to the hub, this part of the blade posed the greatest challenge in shape compounding. It is also the region with the thickest veneer buildup, and thus has the greatest ability to resist vacuum forming forces during the molding process. In addition, the finite, 2.44 m (8 in), length of the veneer sheets gave a high probability that veneer joints would occur in this region. All of these factors made it quite clear that a test of the inboard blade region was a necessary step required to validate the new design methods used. Figure 1 shows the inboard blade cross-sections of the final AOC 15/50 blade design, so that the reader can appreciate the kind of shape transition that was finally used.

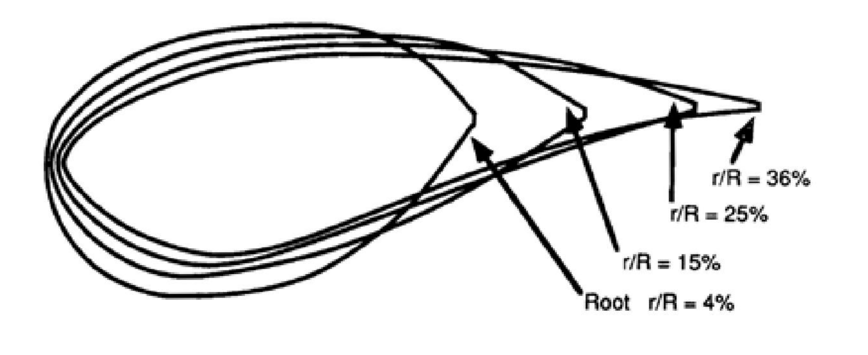

Figure 2. Shape Transition Contours for the Inboard Portion of the AOC 15/50 Blade

To derive the greatest value from a blade fatigue test, it was desirable to test as many features of the blade in a single test as possible. For the AOC 15/50 blade design, the inner part of the blade possess three distinct features that cause stress concentrations, and therefore might limit fatigue performance:

1) The beginning of the root stud thickness buildup
2) The most inboard series of veneer butt joints
3) The first interior veneer dropoff

These features are illustrated in the schematic veneer layout drawing given in Figure 2, which shows each of these features in its appropriate spanwise location but foreshortened in the spanwise direction in order to provide a reasonably sized depiction.

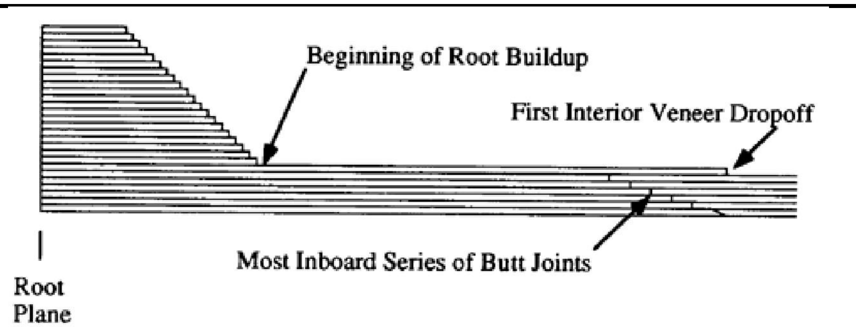

Figure 3. AOC 15/50 Inboard Blade Veneer Layout

By appropriately choosing the length for the test article, from the root plane to the load application point, it was possible to have relatively constant stresses over a long region of the inboard blade, large enough to encompass all of the above features of special interest. Figure 3 shows the computed blade strength as a function of blade radius. The single point load application moments using during the blade fatigue test are also shown on this plot. This graph illustrates the proportional matching of the maximum applied moments and blade design strength over the spanwise region of interest.

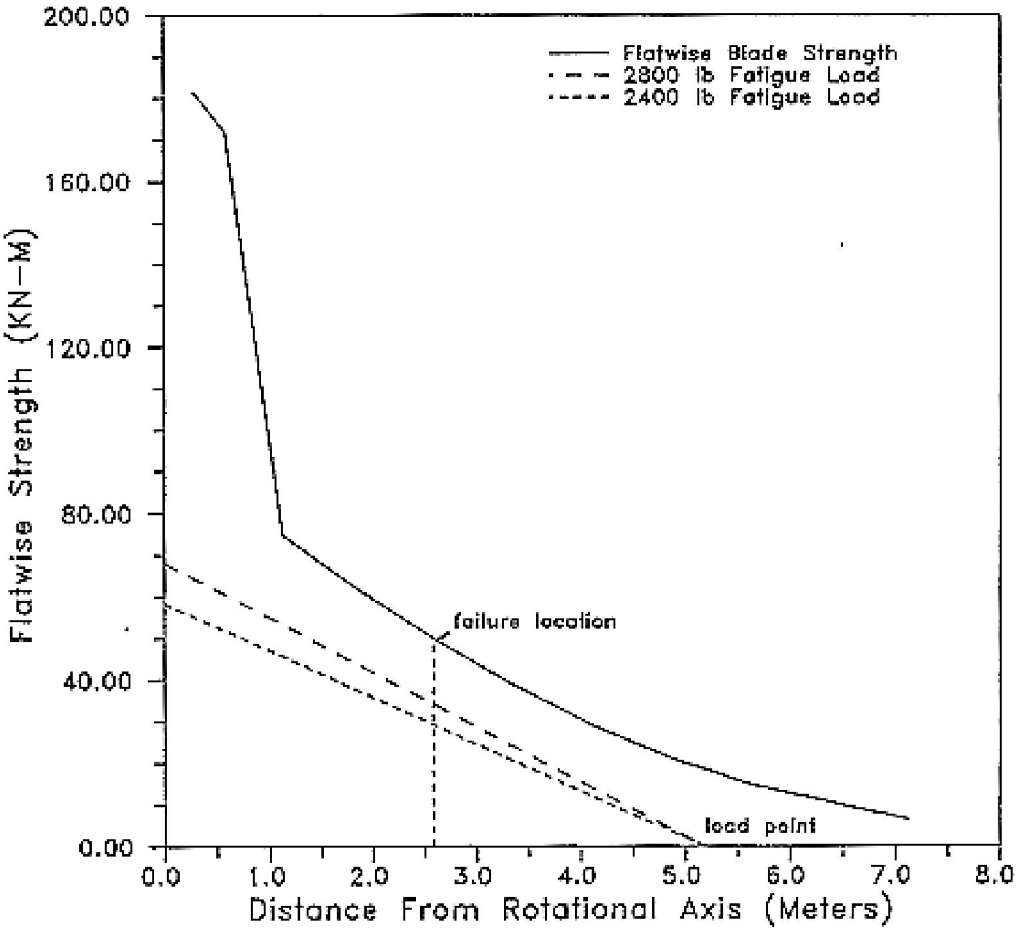

Figure 4. AOC 15/50 Blade Strength and Single-Point Bending Moment Distribution vs. Blade

In order to exercise the blade in fatigue, while allowing for the possibility of a weaker than expected blade due to a strength reducing defect, a block loading test methodology was adopted. This procedure used sinusoidal, constant-amplitude cycle blocks to exercise the blade. With the successful completion of one load block, the maximum load and stress was increased for the next block of cycles. In this way, a fatigue failure can be achieved with a reasonable number of cycles even with a reduced strength condition present, whereas the failure might occur in very few cycles if the assumed full fatigue load were applied initially. This procedure also guards against excessive test durations if the test article proves to be somewhat stronger than predicted. This can be quite important since wood-epoxy material has a relatively flat fatigue slope and a modest change in the strength assumption could result in greatly extended blade life.

Another important feature of the block loading procedure is that this allows test execution in the constant stroke mode. Due to resonance effects in the test specimen as described in a previous paper by Musial [1], it was found that test control using the applied load signal was not practical. With constant load blocks, the stroke required for a given load can be found in a static preloading, and then test segments can be run in stroke control mode. Periodic checks of the load versus stroke relationship were used to assure that the load had not varied significantly. This is generally a quite good assumption with wood/epoxy materials, since little modulus change occurs until the final stages of failure. This assumption held up under the current AOC 15/50 blade test.

Test Execution and Results

The AOC 15/50 blade tested was the first prototype manufactured at Gougeon Manufacturing Corporation (GMC). This blade was trimmed to the desired length, and a specially fabricated interface with bonded fasteners was provided to secure the load application hardware. The blade was mounted to the test stand with a special adaptor plate, for loading in flap bending with the chord-line horizontal at the load application point. The objective was to match the bending moment from the root area out past station 118, approximately 3. 0 m (118 inches) from the rotational axis. This portion of the span possesses all of the key structural features described earlier. The load introduction point was chosen to be at 5.18 m (17 ft), to provide a long region of nearly constant stress encompassing all of the critical design features, as illustrated in Figure 3.

Block loading was applied to the blade using an R = 0.1 stress amplitude. (R is the ratio of the minimum load to the maximum load). The positive R value in this case indicates no reversal of the bending loads. The load sequence began with a load block of 7.12 kN / 0.712 kN (1600 lb / 160 lb) applied for 100,000 cycles. The test was continued by increasing the peak load by increments of 1.78 kN (400 lbs) while maintaining the R = 0.1 load amplitude. This resulted in a 8.90 kN / 0.890 kN (2000 lb / 200 lb) load block for 100,000 cycles followed by a 10.68 kN / 1.068 kN (2400 lb / 240 lb) load block for 250,000 cycles. The 10.68 kN (2400 lb.) load sequence was continued to a quarter of a million cycles to provide a higher cycle baseline to extrapolate the blade's ability to qualify under the Danish fatigue criterion. To pass this standard, the blade would have to survive a 8.01 kN / 0.801 kN (1800 lb./180 lb.) load sequence for 10^7 cycles.

The final failure occurred during the 12.45 kN / 1.245 kN (2800 lb / 280 lb) loading sequence after 55,733 cycles. Based on this test result, preliminary calculations show that the blade probably should be able to survive the Danish qualification test, as will be discussed in the following section. The failure was on the compressive side of the skin (upper surface) and occurred 2.6 m (102.5 in) from the axis of rotation. This put the failure location in the region of the innermost veneer butt joints, one of the areas of critical design features the test was designed to exercise.

Comparative Fatigue Performance

Figure 4 shows the typical fatigue response of a butt jointed Douglas fir laminate in R= 0.1 compression fatigue [2]. This is the material used in the AOC blade, and since failure occurred on the compression side in an R = 0.1 test, this fatigue curve slope can be directly applied to the present test results. It should be noted that the absolute value of stress in not directly applicable, because factors such as size effect and laminate moisture content must be accounted for in going from laboratory material test results to full scale test article results.

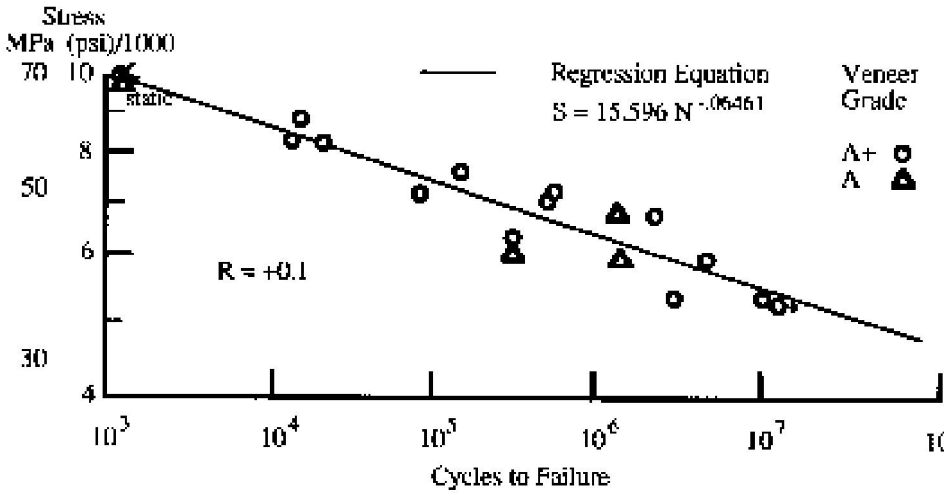

Figure 5. S-N Curve For Butt-Jointed Compression Fatigue of Douglas Fir [2]

Figure 5 - S/N Curve For Butt Jointed Compression Fatigue of Douglas Fir (Reference 2)

Based on this fatigue curve slope and the demonstrated test article strength of 55,733 cycles at 12.45 kN / 1.245 kN (2800 lb / 280 lb) loading, the predicted life at 8.01 kN / 0.801 kN (1800 lb / 180 lb) would be:

(needs the equation)

(8.01 / 12.45) (1/-.0646 1) => 921 times as long,
or,
51,400,00 cycles

This is 5 times in excess of the Danish fatigue acceptance standard, which is based on a constant amplitude loading of 150 N/m^2 of rotor swept area with the load concentrated at 2/3 radius. It should be noted that this calculation is based on only the last load block only and takes no credit for the cycles accumulated in the preceding load blocks. In particular,the 250,000 cycles from the immediately preceding load block could be expected to have contributed significant fatigue damage that is not accounted for in this deliberately conservative calculation to extrapolate fatigue life. While more definitive proof will be determined in subsequent testing to actually demonstrate 10^7 cycle performance, we now have empirically based confidence that such a qualification test will be successful.

Comparison to Predicted Stiffness

As part of the test design procedure, the computed blade stiffness values were used to predict the blade deflection under the chosen loads. These predictions were found to be within a few percent of the measured values. For instance, in the last load block, the deflection was predicted to be 247 mm (9.7 1 in), whereas the measured value at the beginning of this final load block was 252 mm (9.94 in), a difference of 2.3 percent. Given the variables involved in manufacturing and test, and the effect of the preceding 450,000 total accumulated cycles, this is considered to be excellent agreement between computed stroke range, and that measured during test.

Failure Examination Results

Post-test dissection of the test article was performed at the NREL test facility to further investigate the nature of the compression side failure. By carefully cutting through the failure region, a numbered sequence of spanwise sections was provided. Detailed examination of these revealed that compaction and bonding in the joint area where the failure occurred were below typical standards. This may indicate that the additional geometric compounding of the more complex inboard airfoil shapes is having a significant effect on the laminate joint fabrication, and resulting fatigue strength.

This finding is not viewed as a problem, as the blade appears to have achieved the standard certification level of performance in spite of this condition. In addition, the learning provided by this blade test has caused a minor manufacturing process modification to provide significant bonding and strength improvement in this joint area, so that future production blades can achieve even higher performance with negligible increase in cost.

Conclusions

The NREL blade fatigue test provided a validation of the predicted stiffness and deflection values, and a strong indication that the blade design is adequate to meet the Danish fatigue performance levels. Furthermore, it was eminently successful in finding the first limiting feature of the initial fabrication technique, and showing the way to improve fatigue performance in that joint area through minor manufacturing process modification. Use of the block loading technique kept cycle totals, test times, and test costs within reasonable bounds, and use of the constant stress ratio allowed simple extrapolation to higher cycle levels. This both provides confidence that the current design can meet the typical Danish design standard, and helps provide guidance to future tests to elevated cycle levels. While other kinds of fatigue loading may be appropriate to other testing goals, the current choice of block loading is felt to be eminently successful for providing both a first assessment of long term fatigue performance, and an insight into current design hot-spots and potential improvements.

Acknowledgments

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